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Exposure-to-absorbed-dose Conversion for Human Adult Cortical Bone

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The conversion of measured exposure to absorbed dose at a point in bone, under conditions of electron equilibrium, involves a factor (the f-factor) which is proportional to the ratio of the spectrum-averaged photon energy-absorption coefficient for bone to that for air. This paper gives mass energy-absorption coefficients and f-factors for three compositions of human adult compact or cortical bone recommended in publications by the ICRU and the ICRP, for photon energies from 1 keV to 1.5 MeV. Spectrum-averaged f-factors for a number of calibration x-ray beams ranging from 10 to 250 kVp have been calculated and compared to corresponding results obtained with the use of an equivalent photon energy derived from the measured thickness of the half-value layer. At low photon energies ($\leqslant$200 keV), the new f-factor results reflect: (a) the rather large differences due to the differing calcium contents among the recommended compositions for bone: and (b) the generally poor predictions obtained when replacing a broad energy spectrum by an equivalent photon energy.

Introduction

The assignment of dose at a point in a medium from a measurement of the ionizing photon exposure† using an air-equivalent ionization chamber involves a well-known conversion factor that includes the ratio of the average mass energy-absorption coefficients (μ_{en}/ρ) for the medium and for air. Under conditions of electron equilibrium, the dose in the medium D_{med} is given by:

$$D_{med} = M \cdot N_x \cdot \bar{f}_{med}, \tag{1}$$

where M is the ionization chamber reading (in coulombs), N_x is the product of the exposure calibration factor (in roentgens per coulomb) and any other chamber-specific correction or perturbation factors, and

$$\bar{f}_{med} = \left(\frac{\bar{W}}{e}\right) \frac{\int [\mu_{en}(E)/\rho]_{med} E\phi(E)\,dE}{\int [\mu_{en}(E)/\rho]_{air} E\phi(E)\,dE}, \tag{2}$$

where $\bar{W}/e$ is the mean energy expended in air per ion formed. In the integrals of equation (2), μ_{en}/ρ is the mass energy-absorption coefficient, and $\phi(E)$ is the differential fluence spectrum, as a function of the photon energy E, at the point of interest. For a monoenergetic photon beam, f_{med} becomes simply

$$f_{med} = \left(\frac{\bar{W}}{e}\right) \frac{[\mu_{en}(E)/\rho]_{med}}{[\mu_{en}(E)/\rho]_{air}}. \tag{3}$$

A conventional method to reduce consideration of the complete photon spectrum to that of a single photon energy is through the use of an equivalent photon energy derived from half-value layer (HVL) measurements (Johns and Cunningham, 1983). Thus,

$$\mu(\hat{E}) = \frac{\ln 2}{\mathrm{HVL}}, \tag{4}$$

where $\hat{E}$ is the equivalent photon energy and HVL is the thickness of the first half-value-layer.

This paper is concerned with the evaluation of f-factors for human adult bone tissue. These have been calculated here for various recommended compositions of bone tissue using current information on μ_{en}/ρ tabulations. Our results include spectrum-averaged values of $\bar{f}_{bone}$ for a number of x-ray calibration beams; these are compared with corresponding values obtained with the use of an equivalent photon energy derived from HVL measurements.

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†The data in this report can also be used, with minor conversions, when the measured quantity is air kerma.

Table 1. Elemental composition (fractions by weight) assumed for air and adult bone. The mean value of the ratio of atomic number (Z) to atomic mass (A) is also given

	$\langle Z/A \rangle$	H	C	N	O	Na	Mg	P	S	Ar	Ca	Zn
Air	0.49919	—	0.00012	0.75527	0.23178	—	—	—	—	0.01283	—	—
ICRU10b compact bone	0.53010	0.06398	0.27800	0.02700	0.41002	—	0.00200	0.07000	0.02000	—	0.14700	—
ICRP23 cortical bone	0.52130	0.04723	0.14433	0.04199	0.44610	—	0.00220	0.10497	0.00315	—	0.20993	0.00010
ICRU44 cortical bone	0.51478	0.03400	0.15500	0.04200	0.43500	0.00100	0.00200	0.10300	0.00300	—	0.22500	—

Sources of Data

Compositions for human adult bone from widely-recognized compilations have significantly different proportions of calcium, which result in noticeable differences in μ_{en}/ρ and, hence, f_{bone}. ICRU Report 10b (ICRU, 1964) recommends a representative composition for bones in general that includes 14.7%, by weight, of calcium. The recommended composition for cortical bone in Reference Man from Report 23 of the International Commission on Radiological Protection (ICRP, 1975) contains 20.99% calcium;

Table 2. Mass attenuation and mass energy-absorption coefficients ($cm^2\,g^{-1}$) for air and for adult bone. Pertinent K-edge energies are indicated by the chemical symbol to the left of the first column

	Photon energy (keV)	Air, dry		ICRU10b (compact bone)		ICRP23 (cortical bone)		ICRU44 (cortical bone)	
		μ/ρ	μ_{en}/ρ	μ/ρ	μ_{en}/ρ	μ/ρ	μ_{en}/ρ	μ/ρ	μ_{en}/ρ
	1.000×10^{0}	3.605×10^{3}	3.599×10^{3}	3.441×10^{3}	3.435×10^{3}	3.737×10^{3}	3.730×10^{3}	3.779×10^{3}	3.772×10^{3}
	1.072×10^{0}	2.986×10^{3}	2.980×10^{3}	2.863×10^{3}	2.858×10^{3}	3.117×10^{3}	3.111×10^{3}	3.148×10^{3}	3.143×10^{3}
Na	1.072×10^{0}	2.986×10^{3}	2.980×10^{3}	2.863×10^{3}	2.858×10^{3}	3.117×10^{3}	3.111×10^{3}	3.154×10^{3}	3.149×10^{3}
	1.305×10^{0}	1.748×10^{3}	1.745×10^{3}	1.691×10^{3}	1.688×10^{3}	1.846×10^{3}	1.844×10^{3}	1.871×10^{3}	1.869×10^{3}
Mg	1.305×10^{0}	1.748×10^{3}	1.745×10^{3}	1.701×10^{3}	1.698×10^{3}	1.857×10^{3}	1.855×10^{3}	1.881×10^{3}	1.878×10^{3}
	1.500×10^{0}	1.190×10^{3}	1.188×10^{3}	1.165×10^{3}	1.163×10^{3}	1.276×10^{3}	1.274×10^{3}	1.293×10^{3}	1.291×10^{3}
	2.000×10^{0}	5.267×10^{2}	5.262×10^{2}	5.239×10^{2}	5.234×10^{2}	5.774×10^{2}	5.768×10^{2}	5.852×10^{2}	5.846×10^{2}
	2.146×10^{0}	4.302×10^{2}	4.299×10^{2}	4.298×10^{2}	4.293×10^{2}	4.744×10^{2}	4.739×10^{2}	4.808×10^{2}	4.803×10^{2}
P	2.146×10^{0}	4.302×10^{2}	4.299×10^{2}	5.854×10^{2}	5.760×10^{2}	7.078×10^{2}	6.938×10^{2}	7.098×10^{2}	6.961×10^{2}
	2.472×10^{0}	2.852×10^{2}	2.849×10^{2}	4.006×10^{2}	3.946×10^{2}	4.880×10^{2}	4.791×10^{2}	4.892×10^{2}	4.805×10^{2}
S	2.472×10^{0}	2.852×10^{2}	2.849×10^{2}	4.043×10^{2}	3.981×10^{2}	4.938×10^{2}	4.846×10^{2}	4.948×10^{2}	4.857×10^{2}
	3.000×10^{0}	1.616×10^{2}	1.614×10^{2}	2.386×10^{2}	2.353×10^{2}	2.940×10^{2}	2.892×10^{2}	2.944×10^{2}	2.897×10^{2}
	3.203×10^{0}	1.332×10^{2}	1.330×10^{2}	1.988×10^{2}	1.963×10^{2}	2.458×10^{2}	2.418×10^{2}	2.461×10^{2}	2.421×10^{2}
Ar	3.203×10^{0}	1.477×10^{2}	1.460×10^{2}	1.988×10^{2}	1.963×10^{2}	2.458×10^{2}	2.418×10^{2}	2.461×10^{2}	2.421×10^{2}
	4.000×10^{0}	7.721×10^{1}	7.636×10^{1}	1.060×10^{2}	1.048×10^{2}	1.319×10^{2}	1.301×10^{2}	1.321×10^{2}	1.303×10^{2}
	4.038×10^{0}	7.508×10^{1}	7.426×10^{1}	1.032×10^{2}	1.020×10^{2}	1.284×10^{2}	1.267×10^{2}	1.286×10^{2}	1.269×10^{2}
Ca	4.038×10^{0}	7.508×10^{1}	7.426×10^{1}	2.361×10^{2}	2.155×10^{2}	3.183×10^{2}	2.888×10^{2}	3.321×10^{2}	3.006×10^{2}
	5.000×10^{0}	3.975×10^{1}	3.931×10^{1}	1.347×10^{2}	1.248×10^{2}	1.826×10^{2}	1.684×10^{2}	1.908×10^{2}	1.757×10^{2}
	6.000×10^{0}	2.299×10^{1}	2.270×10^{1}	8.186×10^{1}	7.667×10^{1}	1.113×10^{2}	1.040×10^{2}	1.164×10^{2}	1.085×10^{2}
	8.000×10^{0}	9.626×10^{0}	9.446×10^{0}	3.685×10^{1}	3.495×10^{1}	5.034×10^{1}	4.769×10^{1}	5.269×10^{1}	4.987×10^{1}
	1.000×10^{1}	4.897×10^{0}	4.742×10^{0}	1.959×10^{1}	1.869×10^{1}	2.684×10^{1}	2.561×10^{1}	2.809×10^{1}	2.680×10^{1}
	1.500×10^{1}	1.482×10^{0}	1.334×10^{0}	6.121×10^{0}	5.809×10^{0}	8.384×10^{0}	8.005×10^{0}	8.778×10^{0}	8.388×10^{0}
	2.000×10^{1}	6.904×10^{-1}	5.389×10^{-1}	2.695×10^{0}	2.485×10^{0}	3.662×10^{0}	3.434×10^{0}	3.831×10^{0}	3.601×10^{0}
	3.000×10^{1}	3.076×10^{-1}	1.537×10^{-1}	9.098×10^{-1}	7.374×10^{-1}	1.192×10^{0}	1.020×10^{0}	1.240×10^{0}	1.070×10^{0}
	4.000×10^{1}	2.202×10^{-1}	6.833×10^{-2}	4.756×10^{-1}	3.125×10^{-1}	5.900×10^{-1}	4.299×10^{-1}	6.088×10^{-1}	4.507×10^{-1}
	5.000×10^{1}	1.889×10^{-1}	4.098×10^{-2}	3.216×10^{-1}	1.644×10^{-1}	3.770×10^{-1}	2.232×10^{-1}	3.852×10^{-1}	2.336×10^{-1}
	6.000×10^{1}	1.738×10^{-1}	3.041×10^{-2}	2.528×10^{-1}	1.010×10^{-1}	2.827×10^{-1}	1.342×10^{-1}	2.864×10^{-1}	1.400×10^{-1}
	8.000×10^{1}	1.582×10^{-1}	2.407×10^{-2}	1.954×10^{-1}	5.351×10^{-2}	2.056×10^{-1}	6.676×10^{-2}	2.060×10^{-1}	6.897×10^{-2}
	1.000×10^{2}	1.489×10^{-1}	2.325×10^{-2}	1.715×10^{-1}	3.855×10^{-2}	1.751×10^{-1}	4.491×10^{-2}	1.743×10^{-1}	4.586×10^{-2}
	1.500×10^{2}	1.322×10^{-1}	2.496×10^{-2}	1.450×10^{-1}	3.037×10^{-2}	1.443×10^{-1}	3.181×10^{-2}	1.428×10^{-1}	3.183×10^{-2}
	2.000×10^{2}	1.220×10^{-1}	2.672×10^{-2}	1.309×10^{-1}	2.995×10^{-2}	1.294×10^{-1}	3.024×10^{-2}	1.279×10^{-1}	3.003×10^{-2}
	3.000×10^{2}	1.061×10^{-1}	2.872×10^{-2}	1.131×10^{-1}	3.095×10^{-2}	1.113×10^{-1}	3.065×10^{-2}	1.100×10^{-1}	3.032×10^{-2}
	4.000×10^{2}	9.514×10^{-2}	2.949×10^{-2}	1.012×10^{-1}	3.150×10^{-2}	9.955×10^{-2}	3.107×10^{-2}	9.832×10^{-2}	3.070×10^{-2}
	5.000×10^{2}	8.689×10^{-2}	2.966×10^{-2}	9.237×10^{-2}	3.160×10^{-2}	9.086×10^{-2}	3.111×10^{-2}	8.973×10^{-2}	3.073×10^{-2}
	6.000×10^{2}	8.040×10^{-2}	2.953×10^{-2}	8.543×10^{-2}	3.141×10^{-2}	8.402×10^{-2}	3.090×10^{-2}	8.298×10^{-2}	3.052×10^{-2}
	6.620×10^{2}	7.699×10^{-2}	2.936×10^{-2}	8.181×10^{-2}	3.120×10^{-2}	8.045×10^{-2}	3.070×10^{-2}	7.945×10^{-2}	3.031×10^{-2}
	8.000×10^{2}	7.065×10^{-2}	2.883×10^{-2}	7.505×10^{-2}	3.062×10^{-2}	7.381×10^{-2}	3.011×10^{-2}	7.289×10^{-2}	2.973×10^{-2}
	1.000×10^{3}	6.353×10^{-2}	2.789×10^{-2}	6.748×10^{-2}	2.962×10^{-2}	6.637×10^{-2}	2.911×10^{-2}	6.554×10^{-2}	2.875×10^{-2}
	1.170×10^{3}	5.877×10^{-2}	2.705×10^{-2}	6.243×10^{-2}	2.871×10^{-2}	6.138×10^{-2}	2.822×10^{-2}	6.062×10^{-2}	2.785×10^{-2}
	1.250×10^{3}	5.684×10^{-2}	2.666×10^{-2}	6.037×10^{-2}	2.829×10^{-2}	5.937×10^{-2}	2.780×10^{-2}	5.863×10^{-2}	2.745×10^{-2}
	1.330×10^{3}	5.506×10^{-2}	2.627×10^{-2}	5.849×10^{-2}	2.788×10^{-2}	5.753×10^{-2}	2.739×10^{-2}	5.681×10^{-2}	2.705×10^{-2}
	1.500×10^{3}	5.172×10^{-2}	2.547×10^{-2}	5.497×10^{-2}	2.704×10^{-2}	5.408×10^{-2}	2.657×10^{-2}	5.341×10^{-2}	2.624×10^{-2}

while a more recent recommendation for adult cortical bone found in ICRU Report 44 (1989) includes 22.5% calcium, based on the work of Woodward and White (1982) and White *et al.* (1987, 1991). The elemental compositions of these three recommendations for bone are listed in Table 1, along with that assumed for air.

For $\bar{W}/e$ we have used the value 33.97 (± 0.05) $J\,C^{-1}$ taken from the work of Boutillon and Perroche-Roux (1987); this is *ca* 0.35% larger than the value recommended in Report 31 (ICRU, 1979) of the International Commission on Radiation Units and Measurements (ICRU). Using the definition of the roentgen ($1R = 2.58 \times 10^{-4}\,C\,kg^{-1}$), our value for $\bar{W}/e$ becomes $8.764 \times 10^{-3}\,J\,kg^{-1}\,R^{-1}$ (or $8.764 \times 10^{-3}\,Gy\,R^{-1}$).

Values for μ_{en}/ρ are from recent calculations of Seltzer (to be published). These calculations of μ_{en}/ρ have been developed in order to provide up-to-date energy-absorption coefficients that are consistent with the current database (XCOM) of photon interaction coefficients (Berger and Hubbell, 1987) maintained at the National Institute of Standards and Technology (NIST).

Data for the photon fluence spectra from x-ray generators used with standard techniques at NIST have been obtained from Eisenhower *et al.* (1984) and from Seelentag *et al.* (1979). Spectral data applicable to the ^{60}Co sources available at NIST have been obtained from Woolf and Burke (1984) and from Ehrlich *et al.* (1976). Aluminium and copper HVL data are from Lamperti *et al.* (1988).

Results and Discussion

Values of the photon mass attenuation coefficient (μ/ρ) and of μ_{en}/ρ are given in Table 2 for air and for

Table 3. Exposure-to-dose conversion factors for adult bone. Results are given in terms of $100 f_{bone}$, in units of $Gy\,R^{-1}$, for reference bone compositions and for Johns and Cunningham (4th ed)

	Photon energy (keV)	ICRU10b compact bone	ICRP23 cortical bone	ICRU44 cortical bone	Johns and Cunningham 4th ed.
	1.000×10^0	0.836	0.908	0.919	0.824
	1.072×10^0	0.841	0.915	0.924	—
Na	1.072×10^0	0.841	0.915	0.926	—
	1.305×10^0	0.848	0.926	0.939	—
Mg	1.305×10^0	0.853	0.932	0.943	—
	1.500×10^0	0.858	0.940	0.952	0.840
	2.000×10^0	0.872	0.961	0.974	0.856
	2.146×10^0	0.875	0.966	0.979	—
P	2.146×10^0	1.17	1.41	1.42	—
	2.472×10^0	1.21	1.47	1.48	—
S	2.472×10^0	1.22	1.49	1.49	—
	3.000×10^0	1.28	1.57	1.57	1.26
	3.203×10^0	1.29	1.59	1.60	—
Ar	3.203×10^0	1.18	1.45	1.45	—
	4.000×10^0	1.20	1.49	1.50	1.19
	4.038×10^0	1.20	1.50	1.50	—
Ca	4.038×10^0	2.54	3.41	3.55	—
	5.000×10^0	2.78	3.75	3.92	2.81
	6.000×10^0	2.96	4.02	4.19	3.01
	8.000×10^0	3.24	4.42	4.63	3.33
	1.000×10^1	3.45	4.73	4.95	3.57
	1.500×10^1	3.82	5.26	5.51	3.99
	2.000×10^1	4.04	5.58	5.86	4.26
	3.000×10^1	4.20	5.82	6.10	4.44
	4.000×10^1	4.01	5.51	5.78	4.20
	5.000×10^1	3.52	4.77	5.00	3.64
	6.000×10^1	2.91	3.87	4.04	2.97
	8.000×10^1	1.95	2.43	2.51	1.97
	1.000×10^2	1.45	1.69	1.73	1.46
	1.500×10^2	1.07	1.12	1.12	1.07
	2.000×10^2	0.982	0.992	0.985	0.984
	3.000×10^2	0.944	0.935	0.925	0.943
	4.000×10^2	0.936	0.923	0.912	0.934
	5.000×10^2	0.934	0.919	0.908	0.930
	6.000×10^2	0.932	0.917	0.906	0.930
	6.620×10^2	0.931	0.916	0.905	0.929
	8.000×10^2	0.931	0.915	0.904	0.928
	1.000×10^3	0.931	0.915	0.903	0.928
	1.170×10^3	0.930	0.914	0.902	—
	1.250×10^3	0.930	0.914	0.902	0.927
	1.330×10^3	0.930	0.914	0.902	—
	1.500×10^3	0.930	0.914	0.903	0.927

Table 4. Exposure-to-dose conversion factors for moderately-filtered x-ray calibration beams. Results are given in terms of $100 f_{bone}$, in units of $Gy\,R^{-1}$, for three reference adult bone compositions

Spectrum[a]	ICRU10b compact bone	ICRP23 cortical bone	ICRU44 cortical bone
L10(GSF)	3.13	4.26	4.45
L15(GSF)	3.34	4.56	4.78
L20(NIST)	3.56	4.88	5.11
L20(GSF)	3.40	4.66	4.88
M30(NIST)	3.90	5.39	5.65
M30(GSF)	3.85	5.31	5.57
M50(NIST)	4.04	5.58	5.85
H50(GSF)	4.03	5.55	5.82
M60(NIST)	4.05	5.59	5.86
M60(GSF)	4.05	5.59	5.86
S60(NIST)	4.03	5.55	5.82
S60(GSF)	4.03	5.55	5.82
S75(NIST)	3.95	5.43	5.69
S75(GSF)	3.96	5.45	5.71
L100(NIST)	3.69	5.05	5.28
L100(GSF)	3.75	5.13	5.38
M100(NIST)	3.48	4.73	4.95
M100(GSF)	3.45	4.68	4.89
M150(NIST)	2.48	3.23	3.36
M150(GSF)	2.42	3.14	3.26
H150(NIST)	1.25	1.40	1.42
H150(GSF)	1.26	1.41	1.42
H200(GSF)	1.04	1.08	1.08
M250(GSF)	1.17	1.28	1.29
H250(GSF)	0.981	0.990	0.983
^{60}Co lines[b]	0.930	0.914	0.902
^{60}Co therapy source[c]	0.931	0.915	0.903
^{60}Co pool source[d]	0.937	0.924	0.913

[a]The x-ray calibration spectra are designated by the NIST beam codes: the first letter indicates the beam filtration (light, moderate, heavy or special); the number is constant potential in kV [see Lamperti *et al.* (1988)]. The beam code is followed by the initials of the institution at which the spectral measurements were made. NIST spectra are from Eisenhower *et al.* (1984); GSF spectra are from Seelentag *et al.* (1979).

[b]Assuming no scattered component (i.e. only the 1.17 and 1.33 MeV photons).

[c]Assuming a scattered spectrum (20% of total spectrum) for the $10 \times 10\,cm^2$ field in Ehrlich *et al.* (1976).

[d]Assuming a scattered spectrum (44% of total spectrum) from Woolf and Burke (1984).

the three bone compositions considered, at energies from 1 keV up to 1.5 MeV. Resultant values of f_{bone} [from equation (3)] for monoenergetic photon beams are shown in Table 3 and in Fig. 1, along with corresponding results from Johns and Cunningham (1983). The Johns and Cunningham results are based on the compact bone composition from ICRU10b and their somewhat different values of μ_{en}/ρ. As seen from Tables 2 and 3, the larger calcium content of the ICRU44 composition leads to increases in μ_{en}/ρ and in f_{bone} of as much as 45 and 5% with respect to those for the ICRU10b and ICRP23 compositions, respectively. The largest changes are in the energy range from 4.04 to ~100 keV, where the dominant mode of interaction, photoelectric absorption, is most sensitive to relatively large changes in calcium. At higher energies where incoherent scattering is the dominant process, the small differences are of the opposite sign because the Compton scattering coefficient is proportional to $\langle Z/A \rangle$ (see Table 1).

Calculated values of $\bar{f}_{bone}$, using equation (2), for the spectra and bone compositions considered are listed in Table 4. For a given bone composition, results for different ^{60}Co beams, with and without inclusion of the scattered component, are quite close (to within about 1%). The results using x-ray spectra from measurements either at NIST and or at GSF (Seelentag *et al.*, 1979) are also in essential agreement for a given composition. However, the effect on f_{bone} due to the different assumed bone consumptions ranges from about 3% for ^{60}Co to about 45% for the low-energy x-ray calibration spectra.

Because spectra of x-ray beams used in a particular application may not be known, it was thought worthwhile to compare corresponding f_{bone}-values derived from HVL data with those in Table 4. Equivalent photon energy, ($\hat{E}$) and $f_{bone}(\hat{E})$ were determined from equation (4) and (3). Results of comparison with the spectrum-averaged values are given in Table 5. Although reasonably good agreement with the spectrum-averaged values is found for some spectra, errors >20% are found for others. Our results indicate that the use of an equivalent photon energy derived from copper rather than aluminium HVL measurements would be a somewhat better choice. Overall, however, the use of the equivalent photon energy—at least in these cases—appears to be unreliable.

In summary, new μ_{en}/ρ and f_{bone}-values have been computed and compared for three reference bone compositions over a wide range of photon energies. The differences found could significantly affect the estimated absorbed dose derived from exposure measurements, particularly at low energies.

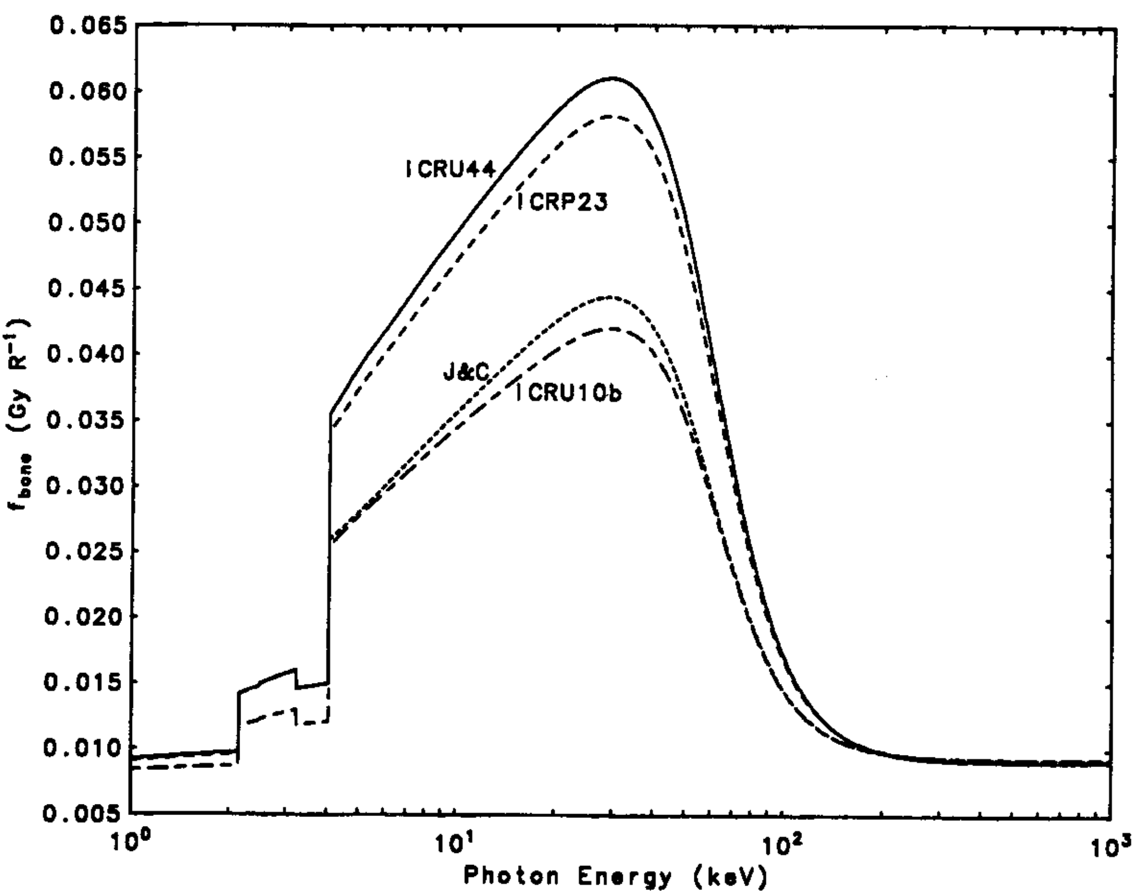

Fig. 1. A comparison of *f*-factors for monoenergetic photons as a function of photon energy for reference bone compositions. The curves are labeled by the reference from which the bone composition was taken (see Table 1); curve labeled J & C is based on the data from Johns and Cunningham (1983).

Table 5. Percent difference of f_{bone}-values obtained with an equivalent photon energy from those obtained by sepctrum averaging. The equivalent photon energies $\bar{E}$ were derived from half-value data of Lamperti *et al.* (1988) for the NIST beams

Spectrum	HVL (mmAl)	$\bar{E}$(keV)	ICRU10b compact bone	ICRP23 cortical bone	ICRU44 cortical bone
A. Aluminum HVL data					
L10	0.029	6.6	−2.6	−2.8	−2.9
L15	0.050	7.9	−3.2	−3.4	−3.5
L20	0.071	8.9	−5.9	−6.3	−6.3
M30	0.36	15.3	−1.5	−1.9	−1.9
M50	1.02	21.8	1.5	1.6	1.5
H50	4.2	36.7	2.0	2.2	2.3
M60	1.68	25.9	3.2	3.4	3.6
S60	2.8	31.2	4.2	4.6	4.7
S75	1.86	26.9	6.3	6.9	6.9
L100	2.8	31.2	13.8	15.1	15.3
M100	5.0	39.5	15.8	17.4	17.4
M150	10.2	58.7	20.6	23.5	24.1
H150	17.0	108	6.6	8.9	9.3
H200	19.8	156	0.7	1.0	1.0
M250	18.5	131.0	−2.5	−3.9	−4.6
H250	22	210	−0.7	−1.0	−1.0
B. Copper HVL data					
M50	0.032	22.4	2.0	2.0	2.1
M60	0.052	26.6	3.5	3.8	3.8
S60	0.089	32.1	4.1	4.4	4.5
M100	0.20	42.6	12.1	13.3	13.3
M150	0.67	65.8	4.0	4.3	4.5
H150	2.5	115	0.6	0.8	0.8
H200	4.1	157	0.5	0.8	0.8
M250	3.2	132.5	−3.4	−5.4	−5.4
H250	5.2	193	0.8	1.2	1.2

In addition, f_{bone}-values are shown to be sensitive to changes in energy below ~200 keV, arguing for the use of spectrum-averaged values.

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